Quaternary Science Reviews 28 (2009) 1131–1146

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Post-fire geomorphic response in steep, forested landscapes: Oregon Coast Range, USA

Molly Jackson, Joshua J. Roering*

Department of Geological Sciences, University of Oregon, Eugene, OR 97403-1272, USA

ARTICLE INFO

Article history:
Received 9 December 2007
Received in revised form 19 April 2008
Accepted 7 May 2008

ABSTRACT

The role of fire in shaping steep, forested landscapes depends on a suite of hydrologic, biologic, and geological characteristics, including the propensity for hydrophobic soil layers to promote runoff erosion during subsequent rainfall events. In the Oregon Coast Range, several studies postulate that fire primarily modulates sediment production via root reinforcement and shallow landslide susceptibility, although few studies have documented post-fire geomorphic response. Here, we describe field observations and topographic analyses for three sites in the central Oregon Coast Range that burned in 1999, 2002, and 2003. The fires generated strongly hydrophobic soil layers that did not promote runoff erosion because the continuity of the layers was interrupted by pervasive discontinuities that facilitated rapid infiltration. At each of our sites, fire generated significant colluvial transport via dry ravel, consistent with other field-based studies in the western United States. Fire-driven dry ravel accumulation in low-order valleys of our Sulphur Creek site equated to a slope-averaged landscape lowering of 2.5 mm. Given Holocene estimates of fire frequency, these results suggest that fire may contribute 10–20% of total denudation across steep, dissected portions of the Oregon Coast Range. In addition, we documented more rapid decline of root strength at our sites than has been observed after timber harvest, suggesting that root strength was compromised prior to fire or that intense heat damaged roots in the shallow subsurface. Given that fire frequencies in the Pacific Northwest are predicted to increase with continued climate change, our findings highlight the importance of fire-induced dry ravel and post-fire debris flow activity in controlling sediment delivery to channels.

1. Introduction

Historical burns in vegetated, mountainous topography highlight the profound erosive potential of fire. Disturbance via fire can alter soil, bedrock, vegetation, and hydrologic properties and induce geomorphic processes distinct from those occurring between burns. These include enhanced hydrophobicity that promotes overland flow erosion (e.g., rilling and gullying), incineration of vegetation that initiates dry ravel (i.e., bouncing, rolling, and sliding) of loose soil clasts on steep slopes, reduction of root reinforcement that increases the likelihood of shallow landsliding, and rapid aggradation of stream channels that may be mobilized as debris torrents in subsequent rainfall events (Swanson, 1981; McNabb and Swanson, 1990; Wondzell and King, 2003). Such fire-related geomorphic processes differ among physiographic provinces due to varying geology, topography, climate, vegetation, and fire regimes (Shakesby and Doerr, 2006).

Recent studies outlining post-fire response in diverse landscapes emphasize the potential dangers of a universal approach for quantifying the contribution of fire to long-term sediment production and transport (e.g., Shakesby et al., 2007). Over the last 50 yr, most research on post-fire erosion has been concentrated in the interior northwest, Rocky Mountain, California, and southwest regions of the United States (DeBano et al., 1977; Cannon et al., 2001; Moody and Martin, 2001; Wohlgemuth et al., 2001; Malmon et al., 2007; Martin, 2007), although a persistent body of literature from Australia and Mediterranean regions has recently been highlighted (e.g., Shakesby and Doerr, 2006; Shakesby et al., 2007). One of the more prominent characteristics that distinguishes post-fire geomorphic response is the extent and persistence of hydrophobic layers that result from alteration and redistribution of organic compounds in near-surface soils. The properties of fire-related hydrophobic layers, which differ in depth and continuity, dictate the efficacy of overland flow erosion that ensues during subsequent storms. Early studies in mountainous chaparral- and scrub-mantled slopes of southern California revealed strong and continuous hydrophobic layers below the topsoil that spawned extensive post-fire overland flow and debris torrent activity during rainfall events in the ensuing winter months (Munns, 1920; Rice

* Corresponding author. Tel.: +1 541 346 5574; fax: +1 541 346 4692.
E-mail address: jroering@uoregon.edu (J.J. Roering).

0277-3791/$ – see front matter
doi:10.1016/j.quascirev.2008.05.003

et al., 1969; Wells, 1981, 1987; Rice, 1982; Spittler, 1995). Rates of erosion associated with this "fire-flood" mode of behavior were extremely rapid, although this process response is far from general, however, as evidenced by field-based studies from a variety of diverse settings (Booker et al., 1993; Shakesby et al., 2007).

In steep, forested landscapes like the Pacific Northwest, USA, fires occur less frequently than in Mediterranean climates and it has been suggested that infiltration rates are sufficiently high to suppress significant post-fire overland flow erosion, although few studies have documented post-fire hydrologic behavior (Swanson, 1981; Agee, 1993; Wondzell and King, 2003). Instead, studies of post-fire response in such regions have focused on the frequency with which fire kills trees, thus driving the decay of root reinforcement in shallow soils that mantle landslide-prone slopes. In simulations by Benda and Dunne (1997b), the stochastic nature of rainfall events that trigger landslides and debris flows following fire dictates the frequency and magnitude of sediment yield. Via this fire-root reinforcement linkage, it has been suggested that timber harvesting may serve as an effective analog for studying how fire influences patterns of erosion; yet no data exist demonstrating that rates of root strength decline mirror those following timber harvest (Nitschke, 2005). In addition, field-based documentation of post-fire erosional processes in steep forested landscapes with highly permeable soils is sparse, so that the fire's contribution to long-term erosion is poorly known. Here, we present field-based observations of post-fire geomorphic response in the Oregon Coast Range, which is characteristic of steep, forested landscapes prone to mass wasting. This study area boasts a significant history of process-based geomorphic research that enables us to couch our analyses of post-fire response in the context of long-term landscape evolution. Fires occurring in 1999, 2002, and 2003 enabled us to quantify the decay of root reinforcement with time as well as document changing hydrologic conditions and fire-related sediment transport mechanisms. Our findings provide a framework for land management decisions given predicted increases in fire frequency in the Pacific Northwest (e.g., Veblen et al., 2003).

2. Study site: Oregon Coast Range

2.1. Geologic background

The central Oregon Coast Range is a humid, soil-mantled, mountainous landscape almost exclusively underlain by the Eocene Tyee Formation (Fig. 1), which has been studied in detail because of its distinct assemblage of sedimentary facies (Lovell, 1969; Chan and Dott, 1983; Heller et al., 1985). Heller and Dickinson (1985) concluded that the Tyee Formation is a sand-rich sequence of turbidite deposits originating from a delta-fed submarine ramp depositional system. Since the late Eocene, the Tyee Formation has been compressed into a series of low-amplitude, gently dipping folds (the maximum dip of bedding along the flanks of folds rarely exceeds 15–20°) oriented north–northeast (Baldwin, 1956). Uplift of the Oregon Coast Range commenced in the Miocene (McNeill et al., 2000) and continues today as evidenced by abandoned wave-cut platforms along the Oregon coast (Kelsey et al., 1996). Rates of rock uplift derived from dating of marine terraces adjacent to our study area (latitude ranging from 43° to 45°) range from <0.1 to 0.3 mm yr^{-1} (Kelsey et al., 1996) and are generally an order of magnitude lower than geodetic uplift rates derived from highway leveling and tide gauge data (Mitchell et al., 1994). Both short- and long-term uplift rates measured along the coast vary locally due to vertical movement along faults, although it is unclear whether these local variations extend a significant distance inland.

2.2. Geomorphic background

Annual precipitation in the western Oregon Coast Range is 1.5–2 m, which occurs predominantly in the winter months. The vegetation is dominated by Douglas-fir (*Pseudotsuga menzeisii*), with lesser amounts of western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*). The topography of the Oregon Coast Range has been characterized as steep and highly dissected with relatively uniform ridge and valley terrain (Dietrich and Dunne, 1978; Reneau and Dietrich, 1991; Montgomery, 2001). Typically, soil is relatively thin (~0.4 m) on hilltops and sideslopes, and thicker (~1–2 m) in unchanneled valleys that act as preferential sources for shallow landslides that often translate into debris flows (Dietrich and Dunne, 1978; Heimsath et al., 2001). Transport on hillslopes is dominated by disturbance-driven processes, such as bioturbation, as extremely high-permeability soils obviate overland flow erosion. Low-order valley networks, on the other hand, are maintained by debris flows that excavate accumulated colluvium and organic material and deposit levees, fans, and terraces in higher-order channels. These flows are a critical sediment transport link between the hillslope and fluvial regimes and are essential in shaping the morphology of the Oregon Coast Range (Benda, 1990; Benda and Dunne, 1997a; Stock and Dietrich, 2003, 2006). The frequency of debris flows initiated by shallow landslides is highly dependent on the status and spatial distribution of tree root networks, which vary with climate and land-use practices (Schmidt et al., 2001; Roering et al., 2003). Following timber harvest, decay of tensile strength for Douglas-fir roots, which is the dominant tree in the Oregon Coast Range, proceeds rapidly (Burroughs and Thomas, 1977).

Most studies of decadal-to-millenial scale rates of sediment production and delivery in the Oregon Coast Range have focused on the cyclic infilling and evacuation of soil in steep, convergent areas (Dietrich and Dunne, 1978; Reneau and Dietrich, 1990; Benda and Dunne, 1997b). Erosion rates generated by short- (~10 yr) and long-term (~5,000 yr) analyses of sediment yield are 0.10–0.15 mm yr^{-1} (Beschta, 1978; Reneau and Dietrich, 1991; Bierman et al., 2001; Heimsath et al., 2001), consistent with rates of coastal uplift (Kelsey et al., 1996) and Holocene bedrock channel incision (Personius, 1995). These studies have been used to argue that an approximate balance exists between rock uplift and erosion in the Oregon Coast Range such that the topographic form may be relatively uniform with time (Reneau and Dietrich, 1991; Roering et al., 1999; Montgomery, 2001).

2.3. Fire-related geomorphic studies in western Oregon

Studies of post-fire geomorphic response in western Oregon have been sparse and relatively local in scope. Following a wildfire in southwestern Oregon, near the Klamath Mountains, Schmidt (1995) measured geomorphic response of hillslopes and channels using erosion pins and measurements of cross-sections. Measurements of dry ravel deposits behind logs yielded local hillslope erosion rate estimates of 1 mm yr^{-1} during the first year, although these rates likely overestimated the broader catchment-averaged response. Because of high infiltration rates and relatively low rainfall intensities, it was argued that geomorphic change following wildfire in the Pacific Northwest is negligible (Schmidt, 1995), although this interpretation may be suspect because the study was conducted on relatively gentle slopes (averaging 11–40%) that are not representative of most regions in Western Oregon.

McNabb et al. (1989) documented decreased infiltration rates in the Siskiyou Mountains of southwestern Oregon following wildfire in a mixed evergreen forest. Infiltration rates were significantly lower on burned slopes compared to unburned slopes, although even the reduced rates were 2–3 times greater than the estimated

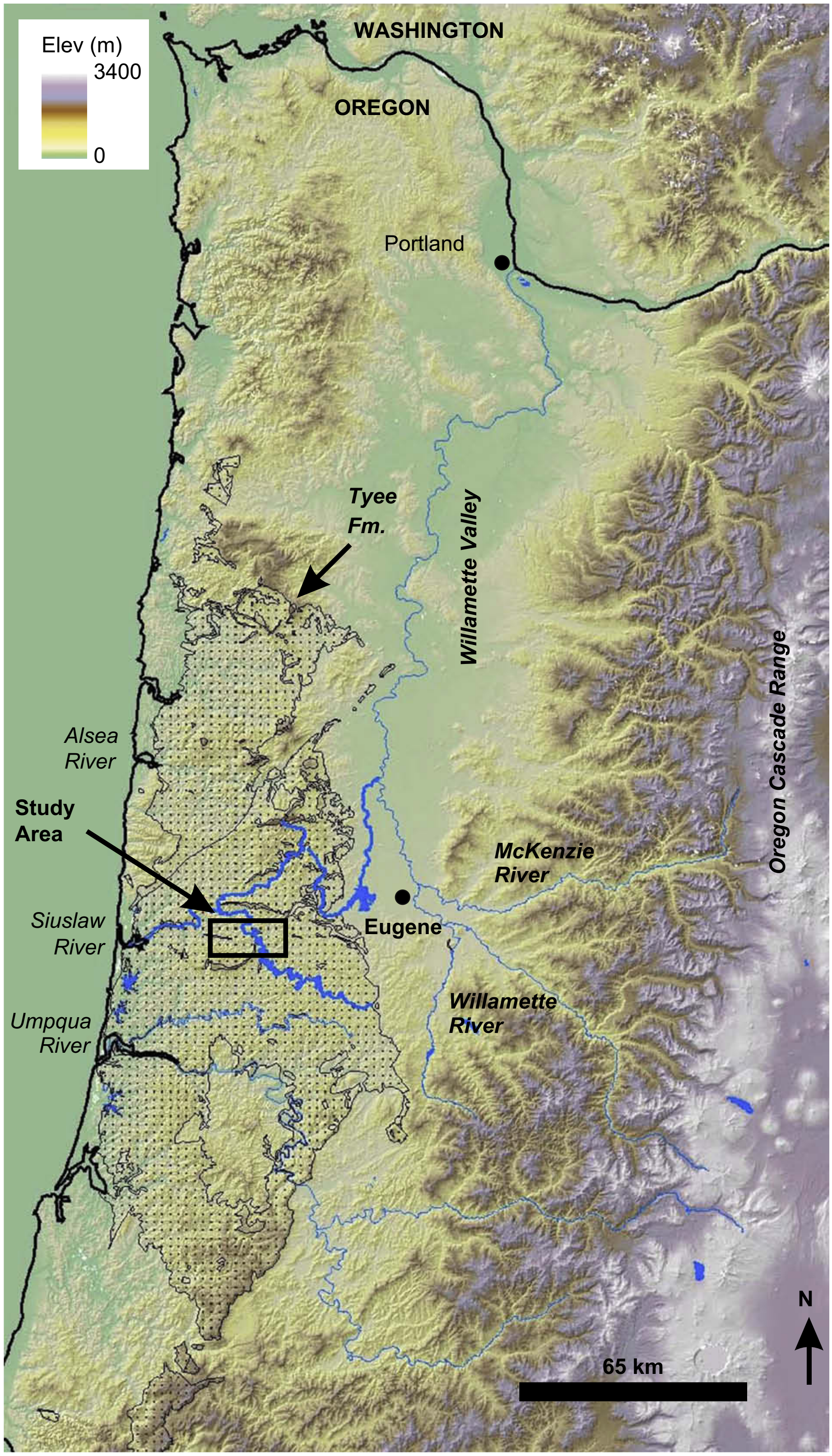

Fig. 1. Study area location map for Western Oregon. The box demarcates our study area shown in Fig. 2. The stippled area denotes the extent of the Tyee Formation, an Eocene turbidite sequence in which our results apply.

rainfall rate for the 100-yr storm (McNabb et al., 1989). The reduction in infiltration was attributed to the development of a water-repellent layer, which disappeared rapidly at the beginning of the rainy season. Using sediment traps, Bennett (1982) quantified rates of soil transport following broadcast burning at harvested sites in the Oregon Coast Range. She observed significant soil transport via dry ravel, and her data demonstrated that burning dramatically increased erosion rates in the first year following fire.

In addition, 65% of the post-fire erosion occurred in the first 24 h following a fire (Bennett, 1982). Mersereau and Dyrness (1972) measured sediment transported primarily by dry ravel after a prescribed burn in the H.J. Andrews Experimental Forest in the western Cascades of Oregon. Sediment traps on 60% slopes collected an average of 0.14 mm yr^{-1}, while 80% slopes collected an average of 0.63 mm yr^{-1}. Sediment transport from south-facing slopes was more than 3.5 times that from north-facing slopes, which may reflect reduced cohesion of soils on drier southern slopes due to decreased bonding between soil grains (Mersereau and Dyrness, 1972; Ravi et al., 2006, 2007). In the second dry season after burning, soil movement was nearly undetectable, due to rapid regeneration of stabilizing vegetation. Their estimates of sediment transport represent minimum values because collection boxes were installed more than 7 months after the burn, presumably after a large pulse of sediment had already been mobilized.

Swanson (1981) proposed that periods of increased erosion resulting from wildfires punctuate the long-term steady erosion rate in western Oregon forests and contribute 25% of the overall sediment yield. Personius et al. (1993) attributed a series of terraces along Oregon Coast Range rivers to aggradation resulting from increased landsliding at the Pleistocene–Holocene transition and speculate that this may have been due to a loss of vegetation resulting from natural vegetation fluctuations or an increase in fire frequency. Roering and Gerber (2005) used Bennett's (1982) ravel transport data and high-resolution topographic data to calibrate a dry ravel transport model and predict the spatial distribution of fire-driven erosion at their Oregon Coast Range site.

2.4. Holocene fire frequency in the Oregon Coast Range

Charcoal and magnetic susceptibility studies on sediment cores from Little Lake, Oregon Coast Range, have been used to quantify the frequency and magnitude of fire over the past 9000 yr (Long et al., 1998). From 9000 to 6850 yr ago, fire intervals averaged about 110 yr, increasing to approximately 160 yr from 6850 to 2750 yr ago, and, most recently (2750–present), the fire interval further lengthened to 230 yr (Long et al., 1998). The lake core also recorded variations in sedimentation rate (perhaps reflecting mass movements in the watershed) and showed an increase around 5000 yr ago. Long et al. (1998) also observed an increase in background charcoal levels about 4000 yr ago, and postulated that the longer fire frequency at that time allowed more buildup of woody fuels, promoting more severe fires and an increase in background charcoal. Interestingly, sedimentation rates and background charcoal levels were poorly correlated, indicating that severe fires were not closely associated with an increased number of sedimentation events.

2.5. Study site descriptions

Three recent wildfires (1999, 2002, and 2003) occurred on harvested and forested slopes within the Siuslaw River Basin, enabling us to examine post-fire geomorphic response in the Oregon Coast Range (Fig. 2). Because the 2003 fire occurred while this study was in progress, we were able to document the immediate response, a critical component of post-fire erosion. Fieldwork was conducted from July through December of 2003.

2.5.1. Austa fire site (1999)

The Austa fire burned approximately 430 hectares of privately owned timber property and Bureau of Land Management (BLM) property near the Austa Bridge on the Siuslaw River in the Oregon Coast Range. It burned from September 28, 1999, until fire crews controlled it on October 8, and created concern regarding sedimentation in nearby streams and proliferation of undesirable brushy species. The fire occurred on very steep, dissected ridges and south-facing slopes underlain by the Tyee Formation. Valley headwalls exceed 45°, and contain exposures of bedrock that were covered by mosses and thin soils and exposed following the fire. Fire intensity varied across the site, ranging from cooler underburns with low tree mortality to hot fires that incinerated forest floors and exposed much mineral soil, scorched boles, removed canopies, and killed entire stands of trees (BLM, 2000). The fire burned clear cuts and stands of trees ranging in age from 11 to 60 yr old, with a few residual 200-yr-old trees. The dominant tree species in the study area is Douglas-fir, with scattered big leaf maple (*Acer macrophyllum*), western hemlock, and white oak (*Quercus alba*); the understory includes native grasses, sword fern (*Polystichum munitum*), bracken fern (*Pteridium aquilinum*), Oregon grape (*Berberus aquifolium*), salal (*Gaultheria shallon*), pearly everlasting (*Anaphalis margaritacea*), poison oak (*Toxicodendron diversilobum*), and Himalayan blackberry (*Rubus armeniacus*). In the fourth summer following the fire, most of the burned trees were still standing, but those in high-intensity burn areas had shed all of their needles. The regenerated understory was dense, and it appeared that some of the big leaf maple had resprouted.

2.5.2. Siuslaw fire site (2002)

The Siuslaw fire burned approximately 348 hectares of managed forest and clear-cut land above the Siuslaw River about 10 km south of the Austa fire site. The fire started on August 17, 2002 and was controlled on November 8. This fire burned BLM property and

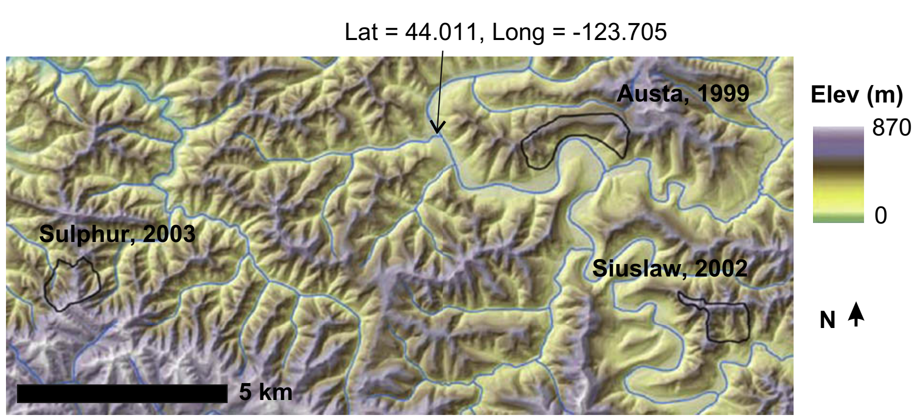

Fig. 2. Local study area map in the central Oregon Coast Range. The area shown is from Fig. 1. The locations of our three burned study sites in the Siuslaw river drainage basin are shown.

private timber property, again creating the potential for an influx of sediment into nearby streams and invasion of brush species and noxious weeds. The topography is steep and dissected with valley headwalls in excess of 45°. The vegetation includes western hemlock and western red cedar, but is dominated by 14- to 52-yr-old Douglas-fir stands with scattered 200-yr-old trees. Fire severity was highly variable, with some stands experiencing 90–100% mortality. Most of the burned trees were still standing 1 yr after the fire, including those with complete canopy removal. In the year following the fire, the understory at the Siuslaw site began to regenerate, but was not as dense as the Austa site. Much of the forest floor was unvegetated, with the mineral soil covered only by a thick blanket of fallen Douglas-fir needles. Sword fern had resprouted from burned plants on the clear-cut slopes, while bracken fern exploited canopy openings resulting from needlefall. The emergency rehabilitation plan facilitated the replanting of seedlings on some slopes, including Douglas-fir, hemlock, and cedar.

2.5.3. *Sulphur Creek fire site (2003)*

The Sulphur Creek fire occurred on privately owned timber lands due west of the Austa and Siuslaw fire sites. It was first reported on June 27, 2003 and was contained on July 5, after burning 263 hectares. Hillslopes average approximately 39–40°, and valley headwalls reach up to 60° in places. Douglas-fir dominates the vegetation mosaic, with some scattered big leaf maple, cedar, and hemlock trees. The understory includes such species as rhododendron (*Rhododendron*), bleeding heart (*Dicentra*), Himalayan blackberry, native grasses, pearly everlasting, sword fern, and salal. The fire burned recently replanted clear-cuts, slopes covered with slash and understory, and managed Douglas-fir stands ranging in age from 19 to 48 yr old. The fire burned severely in some stands, incinerating the forest floor, scorching canopies and trunks, and causing extensive needlefall. On some recently replanted slopes, the fire incinerated all young Douglas-fir, undergrowth, and slash, whereas on slopes that had undergone prescribed burns the fire burned much less intensely, leaving behind only mildly damaged young Douglas-fir. Sword fern and rhododendron had already begun resprouting 3 weeks following the fire.

3. Post-fire hydrophobicity

3.1. *Methods*

To inspect for fire-induced hydrophobicity, we performed water-drop penetration time tests in areas of the 2003 fire site that appeared to have been undisturbed in the weeks following the 2003 fire. We used standards developed by the United States Department of Agriculture Forest Service (Davis and Holbeck, 2001). We gently cleared the sites of fallen needles and dug a trench approximately 10 cm deep. Starting at the top of the soil column on the back wall of the trench, we dropped small beads of water onto the surface of the soil, recording the length of time the water droplet was stable before infiltrating. We then removed a 1-cm layer of soil from the backwall and repeated the process. This method allowed us to ascertain the depth and thickness of water-repellent layers and the severity of hydrophobicity. In addition, we explored the continuity and persistence of hydrophobic soil layers by documenting the spatial pattern of infiltration during the first significant rainfall at the study site in October 2003. To do this, we dug trenches parallel to contour and mapped the wetting front by photography.

3.2. *Results*

At eight of nine test sites in the burned forested areas and at all five sites in the burned clearcut, the water drops perched on subsurface soil layers for more than 60 s, indicating extreme (or strong) hydrophobicity. The depths to the top of the water-repellent layer ranged from 1 to 3 cm, and the thicknesses ranged from 1 to 7 cm (Table 1). Following rainfall events in October and November of 2003, we observed that the water-repellent layer did not appear to promote overland flow erosion. We observed limited rilling only associated with timber-harvest landing sites that did not appear to be related to fire-induced water repellency.

During the first significant rainfall after the fire (October 2003), we dug four 2-m wide trenches along forested hillslopes in the Sulphur site and observed numerous dry soil columns underlying hydrophobic soil layers. Immediately adjacent to these dry soils were patchy wet soil columns revealing local rainwater infiltration up to 20 cm deep (Fig. 3). These zones of infiltration were highly variable in scale, although they did not exceed 30 cm in width (measured horizontally). Although the origin of these localized hydrologic conduits was difficult to constrain, they were sufficiently numerous and large to suppress overland flow at the site.

4. Sediment transport

4.1. *Methods*

To quantify the contribution of fire-driven soil transport to channels, we constructed a sediment budget for our Siuslaw site following the summer 2003 fire. At that site, a shallow landslide initiated a debris flow in November 2001 that scoured the valley floor for nearly 1 km downstream, leaving a largely bare bedrock channel bed. During a series of field trips, we took extensive photographs of the debris flow-scoured valley in 2002 and early 2003. Because the channel did not experience significant infilling between 2001 and the 2003 fire, we were able to document the volume and mechanism of fire-related sediment accumulation in the valley floor. Our initial field visits occurred within 2 weeks of the fire, which occurred at least 2 months before measurable rainfall at the site. We also visited the site several times after substantial rainfall events in October–December of 2003 to document runoff-related transport.

Following the fire, but before the first precipitation, we measured and recorded the dimensions of all fire-related deposits along a 144-m segment of the channel using a tape measure, handheld clinometer, and thin metal dowel to estimate colluvium thickness. In channel reaches containing discontinuous deposits or single large clasts, we estimated numbers and median diameters of cobbles and measured dimensions of boulders. These measurements were summed to determine the total volume of sediment

Table 1
Results of water-drop penetration time tests on intensely burned clear-cut and forested hillslopes.

Site type	Site #	Depth to top of water-repellent layer (cm)	Thickness of water-repellent layer (cm)	Time to absorption (s)	Degree of hydrophobicity
Forested	#1	1	5	>60	Strong
Forested	#2	1	6	>60	Strong
Forested	#3	1	4	>60	Strong
Forested	#4	0.5	3.5	>60	Strong
Forested	#5	0.5	5.5	>60	Strong
Forested	#6	1	4	>60	Strong
Forested	#7	1	1	>60	Strong
Forested	#8	1	0.5	15	Moderate
Forested	#9	0.5	6.5	>60	Strong
Clear-cut	#1	3	2	>60	Strong
Clear-cut	#2	3	5	>60	Strong
Clear-cut	#3	3	7	>60	Strong
Clear-cut	#4	2	6	>60	Strong
Clear-cut	#5	2	5	>60	Strong

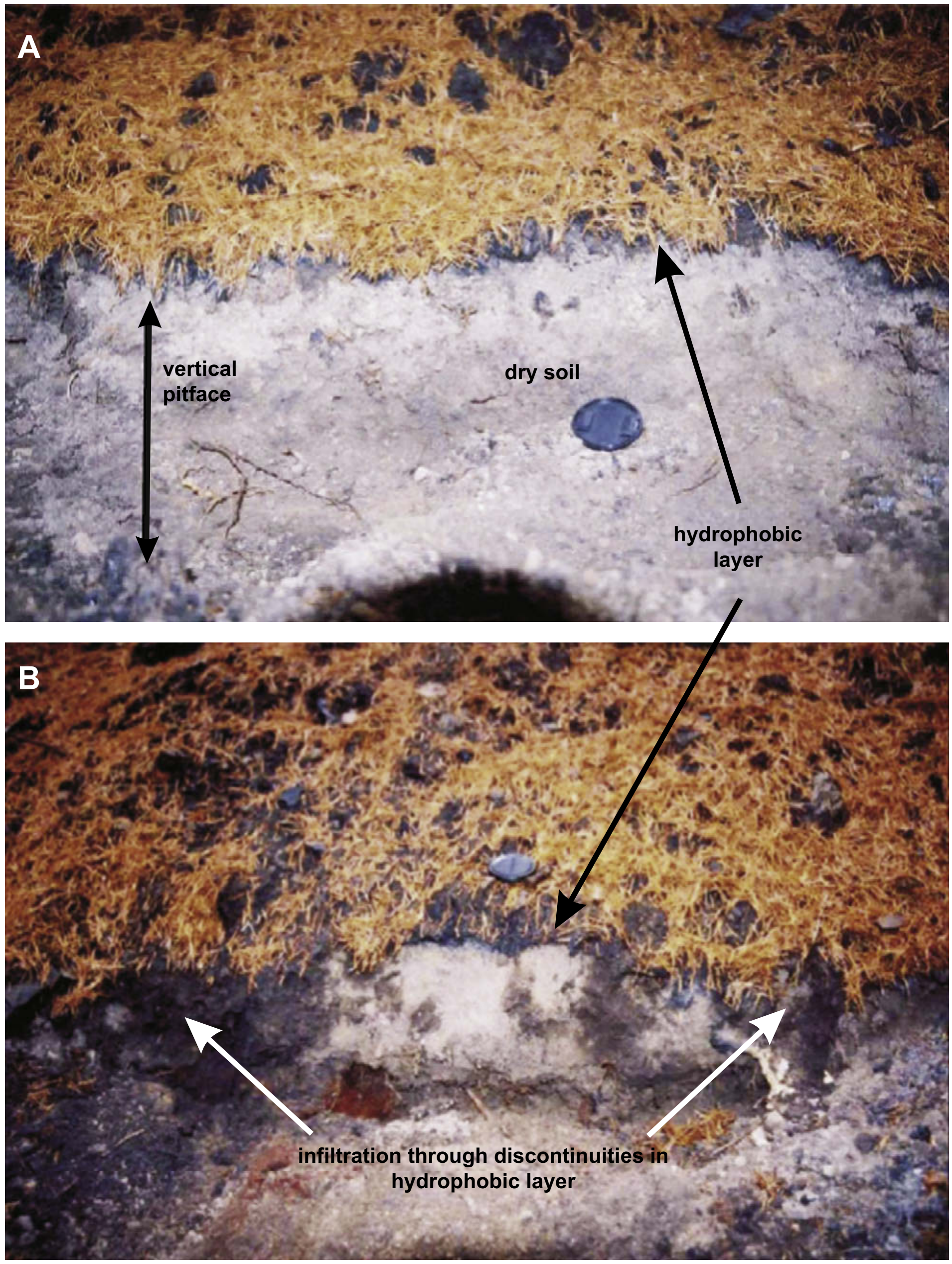

Fig. 3. Photographs of two vertical, contour-parallel trenches dug at the 2003 Sulphur site during the first significant rainfall events of 2003. (A) Dry soil under a hydrophobic layer, see camera lens cap for scale. (B) Infiltration through discontinuities in the hydrophobic layer. These hydrologic discontinuities appear to reflect pre-fire variability in soil organic compounds rather than post-fire bioturbation.

contributed to the length of the channel immediately following the burn. Additionally, we surveyed the surface area of the two opposing hillslopes that contributed material to the valley using a backpack-mounted GPS unit and laser range finder. The average spacing between surveyed topography points was $\sim$5 m, enabling us to produce a more detailed and accurate elevation model than the $\sim$10-m National Elevation Data (NED; available at seamless.usgs.gov). To measure sediment transport into the valley via runoff processes, we installed a sediment trap at the end of our 144-m channel segment using large boulders, steel rebar, and geosynthetic fabric.

4.2. Results

The fire burned the clear-cut hillslopes on both sides of the scoured channel, consuming all vegetation and much of the litter, while leaving behind only large logs, stumps, and mineral soil. Contemporaneous with the fire, colluvium on the hillslopes was mobilized by dry ravel (downslope movement of sediment or organic material by rolling, sliding, or bouncing), and, owing to the efficient coupling of steep hillslopes and low-order valleys in the Oregon Coast Range, a significant volume of ravel deposits accumulated along the valley axis (Fig. 4). Our observations from the burned hillslopes suggest that the fire not only initiated dry ravel via debuttressing of stabilizing vegetation, but also facilitated ravel movement by removing vegetative roughness elements that would normally impede downslope movement. In some areas, the magnitude of transport was sufficient to completely remove the soil mantle. Large patches (100–1000 m^2) of exposed bedrock were observed on slopes at all three of our sites and appear to reflect initially thin soil mantles on steep slopes that experienced significant ravel activity.

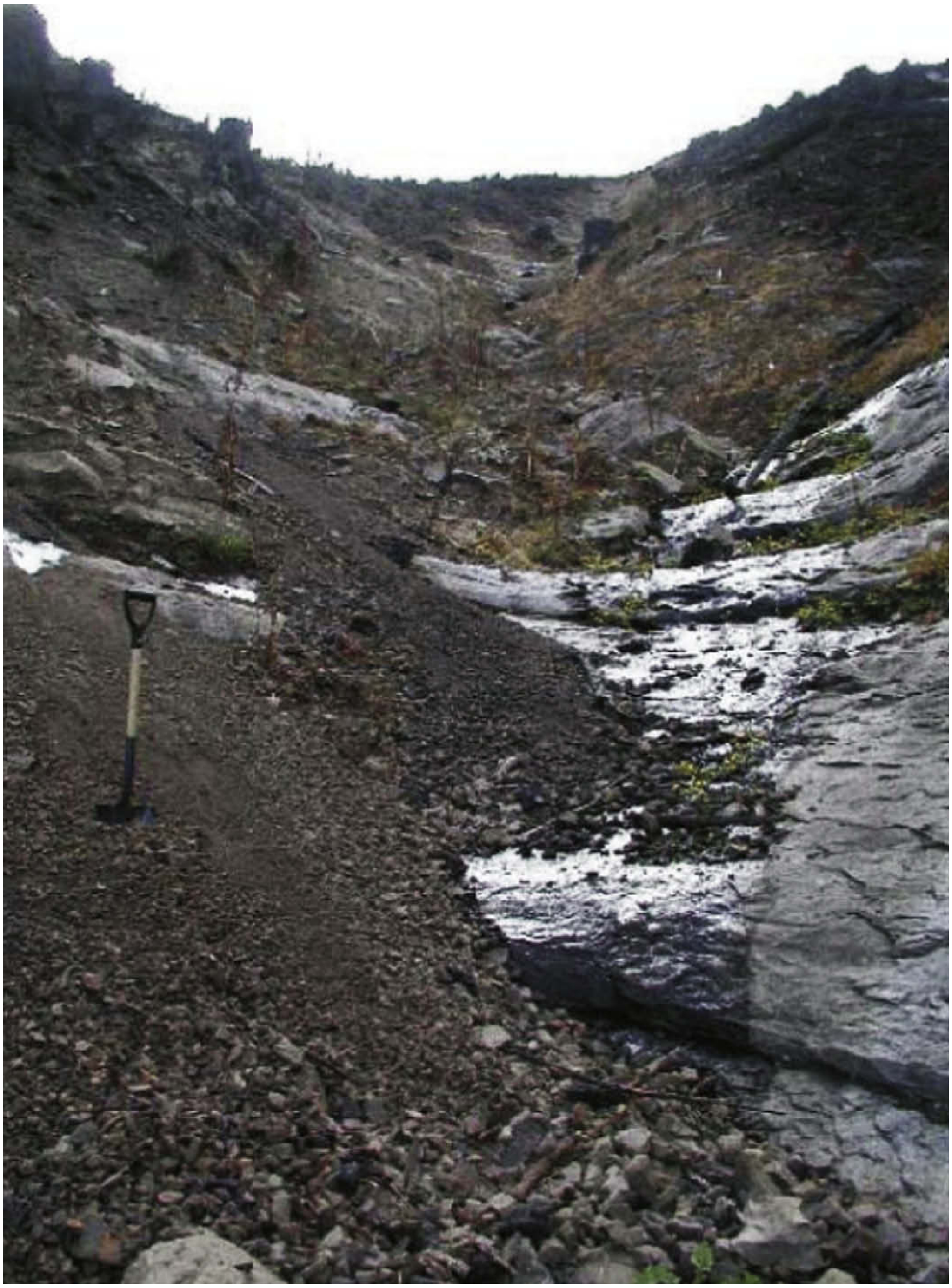

Fig. 4. Photograph of post-fire dry ravel deposits (cones) along Hadsall Creek at our Sulphur fire site (see shovel for scale). Picture taken in July 2003, less than 2 weeks after fire and months before the first post-fire rainfall events. The valley had previously been scoured by a debris flow (November 2001).

Deposits of raveled material were conspicuous on the hillslopes as accumulations of loose colluvium that formed an upslope of stumps or downed logs and lent a streaky appearance to the hillslopes. We observed similar evidence for significant ravel activity on burned forested slopes although we were unable to construct a sediment budget for those portions of the study area. The width of hillslope deposits ranged from 0.5 to 6 m and contained sand- to cobble-sized sediment, with a coarse lag deposit on the surface. The deposits along the channel bed were composed of pebbles to boulders, some of which approached 1 m in diameter (Fig. 4). At the 2003 Sulphur site, more sediment appeared to originate from the west-facing slopes, suggesting a possible role for slope aspect in modulating dry ravel activity. Extensive field inspection confirmed negligible mass transport by runoff processes at our three sites. Because thin soils have limited infiltration capacity, minor sediment transport via runoff did somewhat expand some exposed bedrock areas on isolated steep sideslopes.

In the first 3 months after the 2003 Sulphur fire, we measured 47.4 m^3 of colluvium accumulation along the valley floor (or 0.33 m^3 per meter length of channel). Most accumulation occurred within 2 weeks of the fire, although small ravel events sometimes interrupted our surveying efforts. The west-facing and east-facing slopes that contributed material to the valley had contributing areas and average hillslope gradients of 9300 and 10,050 m^2 and

0.81±0.08 and 0.84±0.08 (mean±standard deviation), respectively. Assuming equivalent ravel contribution from both slopes generates an average surface lowering of 2.5 mm (or 0.0025 m^3/m^2). Given that our survey occurred 3 months after the fire, that observed denudation strictly equates to a lowering rate of 10 mm yr^{-1} or ∼100 times the background erosion rate of the Oregon Coast Range (Reneau and Dietrich, 1991; Heimsath et al., 2001). However, this estimation does not account for the frequency of fire as well as the rapid decline of ravel activity with time. Perhaps a more relevant method for estimating fire's contribution to landscape denudation is to divide our event-based estimate of average lowering by the fire interval. For the Late Holocene fire interval of 230 yr (Long et al., 1998), fire-related denudation averages 0.01 mm yr^{-1} or 10% of the background rate. In the early Holocene, shorter fire intervals (∼110 yr) suggest that fire may have driven 0.022 mm yr^{-1} or 22% of the background rate. These calculations are specific to hillslope conditions at our study site and assume that the pool of colluvium is replenished between fires.

Hillslopes at both the Siuslaw 2002 and Sulphur 2003 sites exhibited the signature of pervasive dry ravel activity (Fig. 5). Along low-gradient hilltops, in-situ charcoal from the fires (seen as dark colors) mantled the slopes, reflecting negligible clast/soil mobilization via dry ravel. In contrast, steep sideslopes exhibited a much lighter color (associated with mineral soil), indicating significant disruption and displacement of near-surface layers via dry ravel (Fig. 5). After about 1 yr, this distinctive pattern was obscured by vegetation regrowth. Our observations are consistent with process-scale studies of dry ravel which show that transport and erosion increase rapidly for slope gradients above ∼0.75 (which approximates the range of friction angles for poorly sorted colluvium, although values likely vary owing to heterogeneous soil and biomass properties) (Fig. 6) (Anderson et al., 1959; Krammes, 1960; Mersereau and Dyrness, 1972; Bennett, 1982; Gabet, 2003). To estimate the ubiquity of such steep, ravel-prone slopes in the Oregon Coast Range underlain by the Tyee Formation, we estimated the distribution of slopes angles using a 10-m DEM. Because DEM-derived slope angles consistently underestimate field-based slope estimates, we compared field and DEM-derived slope values and identified ravel-prone slopes as those with gradient values exceeding 0.7 using a 10-m DEM. We then used a 500 m-radius moving window to estimate the fraction of adjacent terrain with ravel-prone slopes (i.e., fraction with gradient >0.7) (Fig. 7). Fig. 7 shows numerous locales in the central Oregon Coast Range for which more than 50% of the local slopes exceed 0.7 (shown by warm colors), suggesting that fire-driven sediment flux may be a significant component of the sediment budget in these areas. Because debris flow source areas (i.e., unchanneled valleys) constitute a relatively small proportion of the landscape (<10%), this calculation highlights the substantial role that dry ravel may play in delivering sediment to low-order valleys, where it is subsequently mobilized by fluvial or debris flow activity. Several factors control slope distributions in the central Oregon Coast Range, including lithologic variation within the Tyee Formation, deep-seated landsliding, drainage capture, and variable baselevel lowering via differential channel incision (Roering et al., 2005; Almond et al., 2007).

Unfortunately, we were unable to obtain sediment yield data from our debris dam because it was partially demolished by a small debris flow. The debris flow initiated on December 13, 2003, near the initiation site of the November 2001 debris flow, and scoured and re-deposited much of the post-fire sediment in the channel. The rainfall event associated with this event featured 2.5 in of rain in a 24-h period at a nearby weather station (∼50 km distance). Despite the damage to our debris dam, we observed several cubic meters of fine-grained material compounded behind the dam. This material was derived via fluvial mobilization of dry ravel deposits along the channel axis before the debris flow. None of our sites exhibited any indication of debris flow initiation through the mobilization of in-channel deposits.

5. Post-fire root strength decline

Empirical studies have shown a rapid decline in root tensile strength following timber harvesting (Burroughs and Thomas, 1977; Gray and Leiser, 1982; Gray and Sotir, 1996), but to our knowledge no studies have directly investigated changes in root strength following fire. Timber harvesting has been shown to increase landsliding rates after 4–10 yr (see reviews in Wu, 1984, 1995; Schmidt et al., 2001). Although numerous studies suggest that increases in landsliding after fire may mimic those following timber harvesting (Swanson, 1981; McNabb and Swanson, 1990; Benda and Dunne, 1997b), field documentation is sparse. To estimate root strength decline after wildfire, we quantified root tendrile strength at our three fire sites.

5.1. Effects of fire on tree roots

Intense fires can damage the crowns, boles, and root structures of trees, which often leads to the death of the trees and subsequent loss of root strength, increasing the propensity for shallow landslides and debris flows. Wildfire can damage or kill trees in three primary ways: by scorching the crown, lethally heating the cambium, or lethally heating the roots (Agee, 1993). Fire damage to a tree considerably impacts photosynthesis, making it more susceptible to insect attack or disease. After such damage, much of a tree's photosynthetic energy is used to repair foliage and regrow damaged tissues in the cambium or root structure, inhibiting the tree's capacity to produce defensive chemicals to ward off insects or disease. If the foliage is damaged or removed by fire, this further compromises the tree's ability to photosynthesize (Scott et al., 1996). Roots near the soil surface can experience first-order damage, such as scorching or lethal heating, which may contribute to the death of the tree shortly after a fire. Roots may also experience second-order decay coincident with the death of a tree due to other injuries sustained to the foliage or cambium. Roots in the upper 5–10 cm may experience lethal temperatures during intense fires, damaging tree tissue (Swezy and Agee, 1990). Because heat is concentrated in burning boles, proximal roots in the shallow soil often sustain significant fire damage.

5.2. Methods

At our three fire sites, we quantified root strength and root distribution with depth. We hand-dug soil pits only in intensely burned stands of Douglas-fir, ranging in age from 40 to 60 yr with scattered older trees. We dug pits equidistant from surrounding trees and avoided large taproots as abundant smaller roots branching off taproots create localized high root densities. Intensely burned older stands were identified based on total loss of canopy foliage and complete incineration of understory and forest floor. At each site, slope was measured with a hand-held clinometer, scorch height and percent of canopy burned were estimated, and the composition of the forest floor was observed. We also documented the species, diameter, and spacing of trees surrounding each pit.

We hand-dug the soil pits, orienting them parallel to a slope with a rectangular back wall with two triangular sidewalls. All pits were ∼1.0 m deep and 1.0 m wide. We extracted all roots exposed in the three walls and recorded their species, vertical depth, diameter including bark (measured with a micrometer), and the force required for tensile failure. Douglas-fir roots were identified based on their characteristic orange inner bark, while other roots

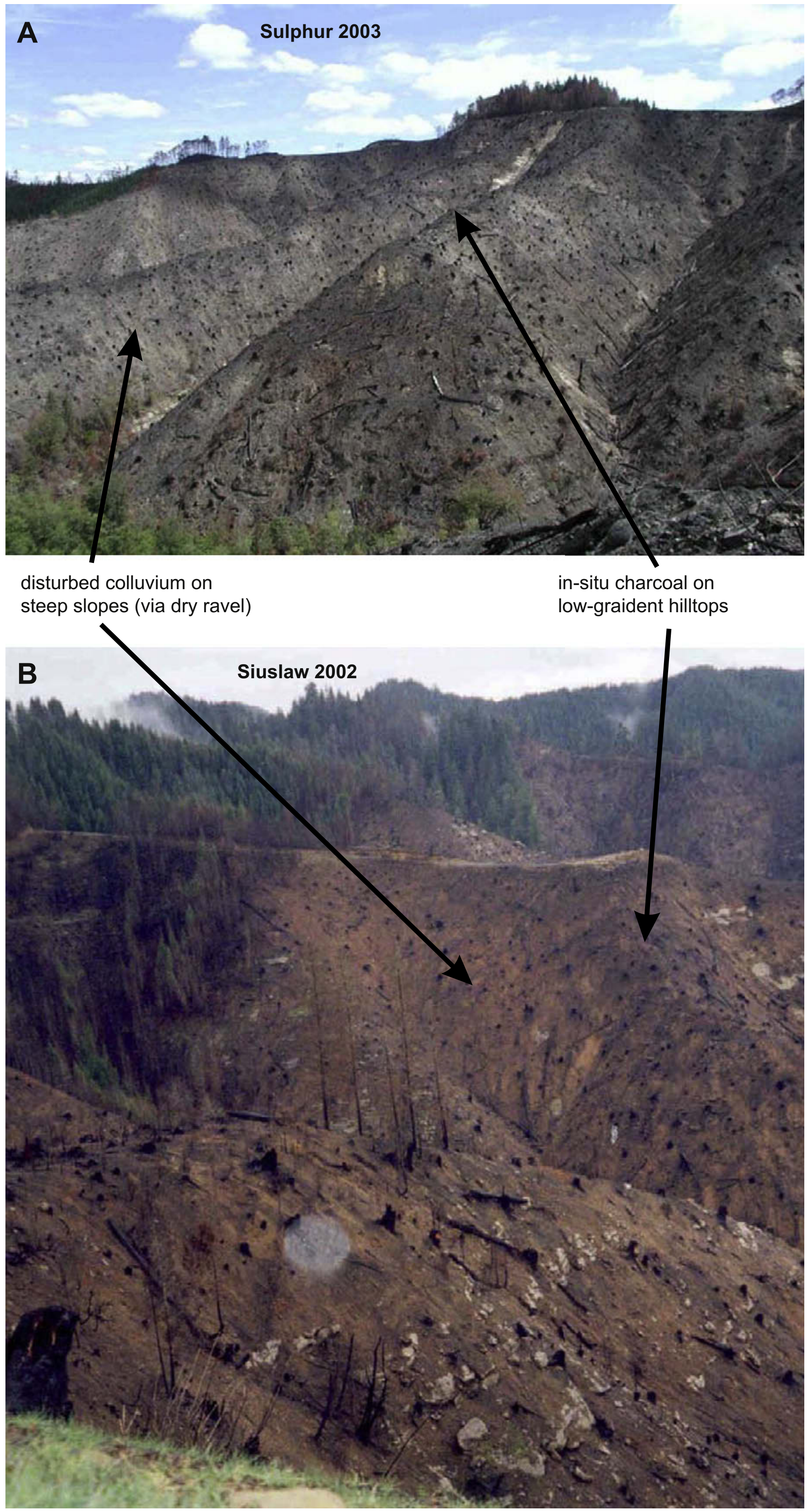

Fig. 5. Photographs of post-fire modification of steep slopes at 2003 Sulphur and 2002 Siuslaw fire sites. Dry ravel activity along steep slopes suppressed preservation of charcoal and shows the distribution of ravel-prone slopes.

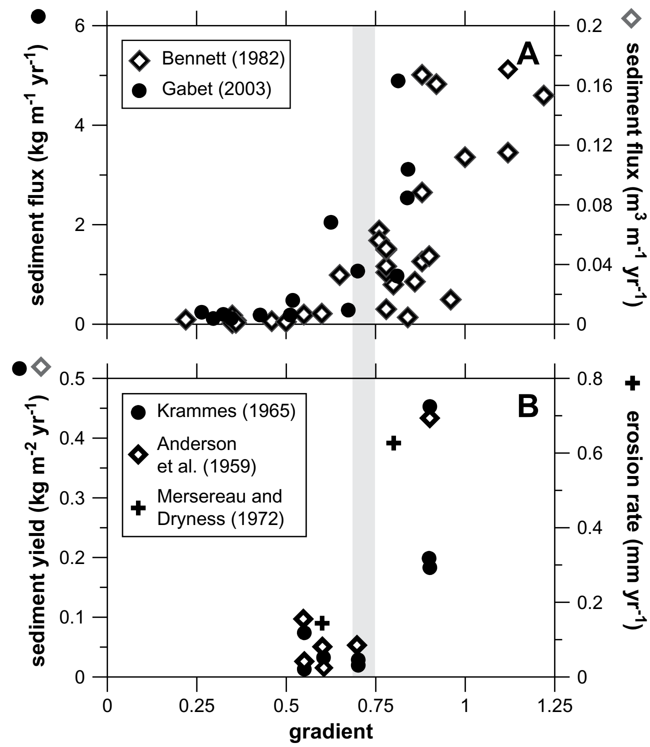

Fig. 6. Relationship between hillslope gradient and erosion and transport rate via dry ravel activity. A threshold of ~0.75 (or 75%) appears to separate low and rapid mass transport in each study. The vertical axes associated with each dataset are expressed by the plot symbols shown above the appropriate axis label.

were excavated to their source plant for identification or simply classified as "non-Douglas-fir" when source plants were too charred to identify. We measured root tensile strength by attaching one end of a root tendrile to a 20-kg spring-loaded scale and pulling the other root end until failure. We measured load at failure for roots up to 7 mm in diameter. If a root slipped from the clamp or broke at the point of attachment, the root was not used in analysis.

5.3. Results

Consistent with previous studies on root diameter–strength relationships (e.g., Schmidt et al., 2001), root strength (or load at failure) increases nonlinearly with root diameter at each of our three sites (Fig. 8). We fit a second-order polynomial to the diameter–strength data for each of the three sites, enabling us to explore decay as a function of diameter. We used the polynomial fits shown in Fig. 8 to calculate the strength for three representative root diameters (2, 4, and 6 mm) and then plotted the variation of strength with time; the decline was particularly rapid in the first year and slowed by the fourth year, consistent with post-harvest decay trends. In addition, the rate of decay increased with root diameter, also consistent with post-harvest studies (Fig. 9). As expected, our root strength values are universally lower than those for healthy, live Douglas-fir roots in the Oregon Coast Range (Schmidt et al., 2001) (Fig. 10). Interestingly, however, strength values for the Sulphur 2003 fire site show a substantial reduction only 1 month after fire. This rate of decay exceeds that observed after timber harvest and suggests that roots at the Sulphur 2003 site may have been compromised before the fire via infestation, infection, logging damage, or other factors. Alternatively, fire damage to shallow roots, which make up a large fraction of roots at the Sulphur site, may have reduced root strength.

Root densities at the three fire sites, measured using the ratio of root area to the area of soil exposure, A_r/A_s, varied between 10^{-4} and 10^{-3} (Fig. 11). All sites show that root area is concentrated in the upper ~25 cm of the soil column. The 2002 Siuslaw site had notably higher root density throughout the soil profile than did the 2003 Sulphur or 1999 Austa sites. These values are similar to those measured by Schmidt et al. (2001), in industrial forests in the Oregon Coast Range (10^{-3}–10^{-4}). In natural forests, root densities almost universally exceed 10^{-3}, further suggesting that our sites have been altered by fire and/or the legacy of timber harvest. The abundance of roots for the 2003 site (55–70 roots m^{-2} soil) was similar to that for the 2002 Siuslaw site (76–79 roots m^{-2} soil), a pattern that reflects the abundance of small roots at the 2003 Sulphur site. The 1999 Austa fire site had a root abundance of 27 roots m^{-2}, much lower than that of the other sites. The fraction of Douglas-fir roots in the soil pits decreased with time since fire (Fig. 12), signaling the emergence of regenerative species within a few years after fire. These species include swordfern, pearly everlasting, big leaf maple, Oregon grape, big leaf maple, salal, and Himalayan blackberry.

6. Discussion

Our results suggest that the primary geomorphic consequences of fire in the Oregon Coast Range are dry ravel and root strength decline; we observed sparse evidence for runoff-related erosion at our three study sites. The high infiltration rates of the Oregon Coast Range soils also appear to disfavor debris flow initiation via entrainment of ash, soil, and debris along valley axes that is commonly observed in other landscapes (e.g., Cannon et al., 2001). Instead, our findings appear to highlight the role of shallow landslide-initiated debris flows in sculpting the landscape. Such debris flow activity primarily depends on spatial and temporal patterns of root reinforcement, which are heavily influenced by fire (as well as rainfall duration and intensity). Debris flow mobility and erosivity depend on sediment loading along runout pathways (Benda, 1990; Lancaster and Hayes, 2003). Specifically, higher rates of bulking (i.e., sediment loading in channels) should increase the length of the debris flow snout that imparts inertial energy and erodes the channel bed (Stock and Dietrich, 2006). As such, the sequence of rapid post- and syn-fire valley aggradation via dry ravel and the subsequent increased likelihood of debris flows several years after fire via reduced root reinforcement suggest that fire-driven processes may enhance the role of debris flows in shaping the Oregon Coast Range. The December 2003 debris flow at our Sulphur fire site effectively removed nearly all fire-related deposits that had accumulated in the valley floor via dry ravel. In addition, dry ravel activity on slopes surrounding zero-order basins may promote infilling of colluvial wedges that tend to serve as shallow landslide source areas, thus promoting slope instability and hollow evacuation.

Although we do not address channel responses to wildfire in this contribution, literature on the subject is plentiful, revealing complicated patterns of response (Spina and Tormey, 2000; Benda et al., 2003; Legleiter et al., 2003). Low-order portions of the Oregon Coast Range tend to exhibit small valley widths with steep adjacent sideslopes such that sediment is efficiently conveyed to the valley network. A recent study of sediment residence time in Oregon Coast Range headwater catchments suggests that headwater debris deposits are preferentially stored (rather than evacuated) such that the signature of debris flow transport following fire may be muted to downstream areas (Lancaster and Casebeer, 2007). As such, sedimentation and paleo-fire records such as those in Little Lake, OR, may include significant lags in sediment and charcoal conveyance.

Our observations and analysis support the suggestion that background erosion rates in the Oregon Coast Range are punctuated by periods of accelerated erosion following wildfire (Swanson,

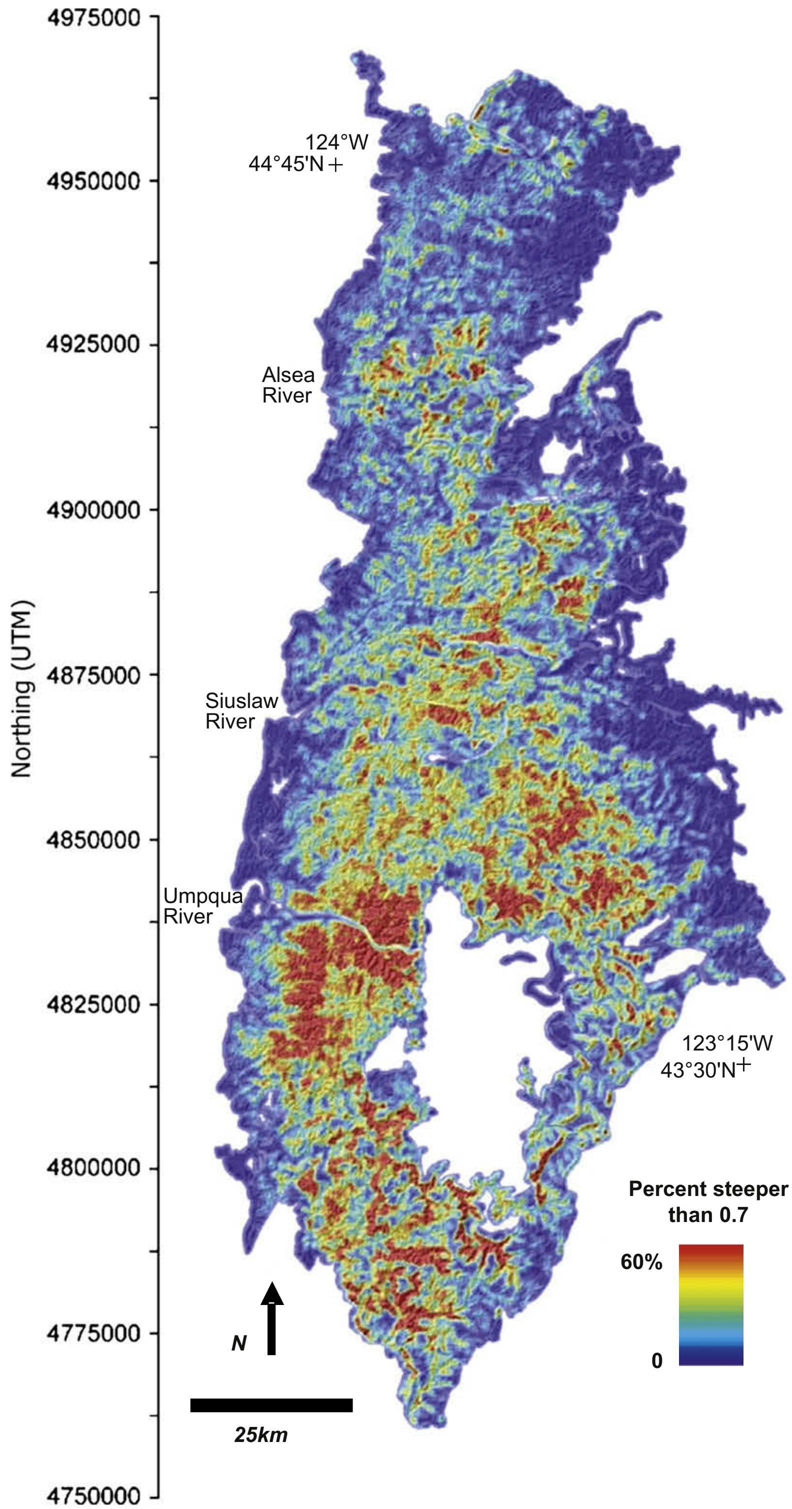

Fig. 7. Map showing the fraction of local terrain (within 500 m) with gradients greater than 0.70 (70%). Map area corresponds to the extent of terrain underlain by the Tyee Formation as shown in Fig. 1. Warm colors reflect regions for which the majority of slopes exceed 70% and are thus prone to rapid post-fire dry ravel activity.

1981; McNabb and Swanson, 1990). Recognition of these periods of highly accelerated erosional episodes is critical in the calculation of long-term erosion; estimates of erosion calculated using stream sediment yields will not capture these short, but highly effective periods of erosion and result in low estimates of long-term erosion. Calculating erosion rate by using infilling of hillslope hollows (Reneau and Dietrich, 1991) or cosmogenic nuclides (Reneau et al., 1990; Heimsath et al., 2001) is more likely to capture discrete and substantial erosional events associated with fire. Combining Oregon Coast Range fire intervals and our measurements of erosion due to dry ravel indicates that post-wildfire dry ravel accounts for a minimum of 5–20% of total long-term erosion in many portions of the Oregon Coast Range. This result is consistent with the findings of Swanson (1981), who indicated that fire may contribute ~25% of the long-term sediment flux in western Oregon. Because we measured only the first 3 months of sediment accumulation in the

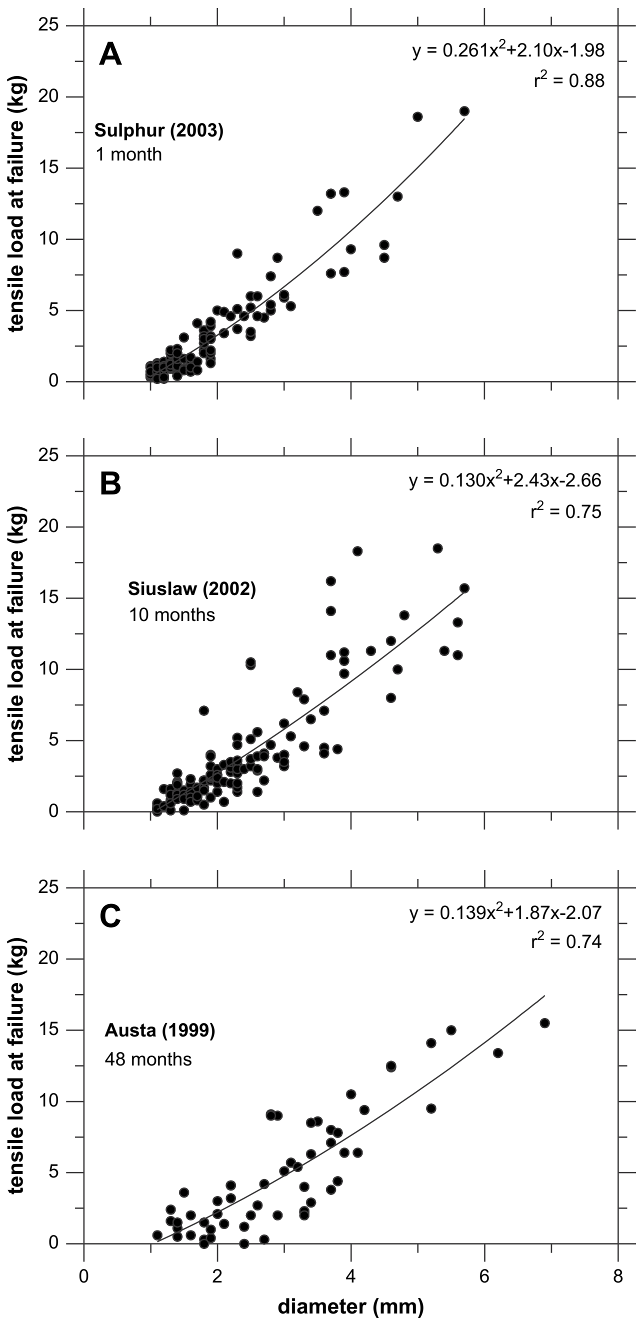

Fig. 8. Relationship between root diameter and tensile load at failure for our three study sites. Each site reflects a different time period since fire. We fit a second-order polynomial to each dataset, and the regression parameters are shown.

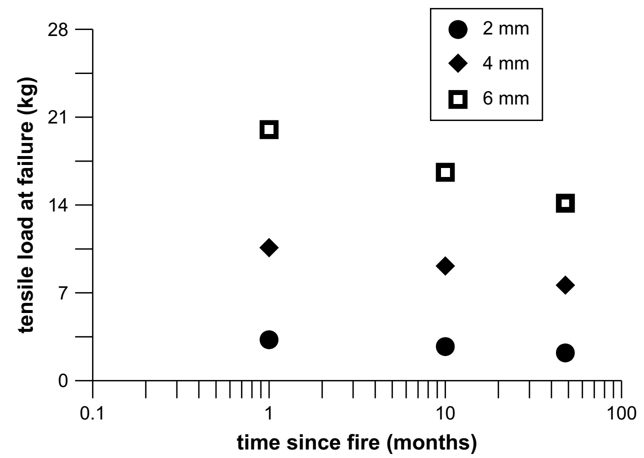

Fig. 9. Log-linear plot of root strength (defined as tensile load at failure) decline for roots of varying diameter (calculated using the polynomial equations shown in Fig. 8). The largest roots experienced the most rapid decay.

channel, total erosion due to dry ravel may account for more than 20% of total erosion in steep, ravel-prone locales of the Oregon Coast Range, although it is difficult to extrapolate these results given variations in fire severity and frequency and management history. In the early Holocene, fires were more frequent and may have been less severe (Long et al., 1998), further complicating the extrapolation of our results. Another cause for ambiguity is that our estimated erosion rates were derived from clear-cut hillslopes perched above the debris flow-scoured valley floor. Substantial logging debris ('slash') was present on the hillslope before the fire, possibly fueling a more intense fire than would have occurred in a 'natural' forest. Nonetheless, our documentation of forested portions of the 2003 Sulphur fire revealed abundant dry ravel deposits on the upslope side of trees and in depressions of varying scale. Unfortunately, these forested sites did not afford an opportunity to construct a sediment budget; so we were unable to directly compare dry ravel transport across harvested and forested slopes. Previous studies highlight the predominance of steep soil-mantled hillslopes throughout Western Oregon (Montgomery, 2001), suggesting that fire-driven dry ravel may account for a substantial fraction of the long-term average sediment production in the region.

Measurements of dry ravel erosion ($\sim 0.0025\,m^3/m^2$) at our study site are similar to those calculated at four southern California sites (Krammes, 1960; Rice, 1982; Florsheim et al., 1991). Doehring (1968) measured voluminous dry ravel deposits at the base of 0.72 and 1.07 gradient slopes, the steeper of which yielded an extremely high event-based lowering of $0.16\,m^3/m^2$. Schmidt's (1995) Klamath site dry ravel measurement of $0.001\,m^3/m^2$ is lower than our estimates, likely because the contributing slopes had slopes of 19–40%. Because they installed sediment traps 7 months after fire, Mersereau and Dyrness' (1972) reported lowering values of 1.4×10^{-4}–$6.3\times10^{-4}\,m^3/m^2$ are an order of magnitude lower than our data. In their study, a prototype sediment trap installed 2 months before the rest of the traps collected more sediment in those 2 months than it did in the following 16 months. The rapid erosion rates measured at our 2003 site occurred within months of

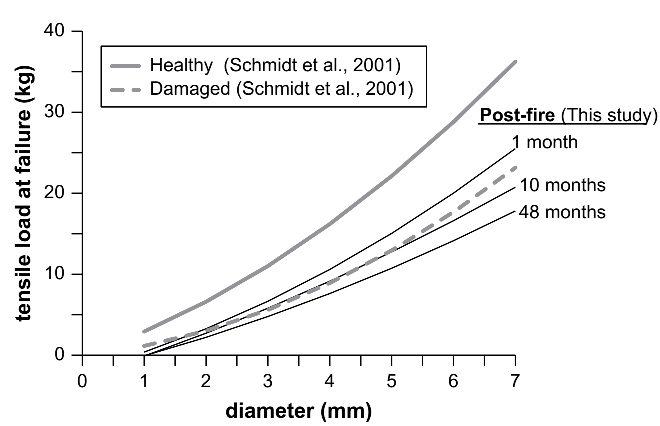

Fig. 10. Comparison of root diameter–strength curves for our three study sites (shown with thin black lines) and previous data from Schmidt et al. (2001) for healthy (thick, solid gray line) and damaged (thick, dashed gray line) Douglas-fir roots. Root strength for our 2003 Sulphur site was much lower than expected compared with post-harvest rates of strength decline.

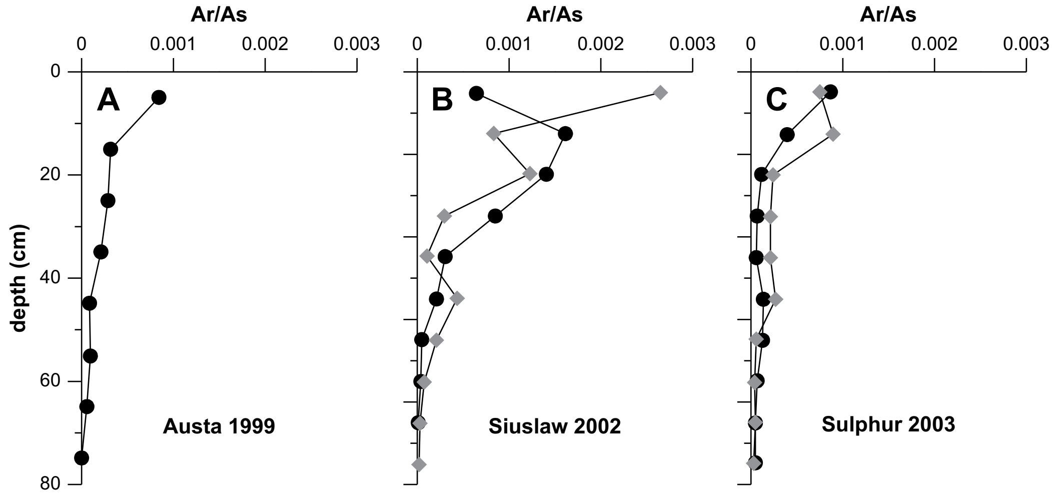

Fig. 11. Profiles of root area density for our three study sites, including one pit at the 1999 Austa site and two pits at each of the 2002 Siuslaw and 2003 Sulphur sites.

the fire and appeared to slow considerably in the second year as dry ravel deposits were not perceptible along the scoured flow valley axis in early 2004. Vegetation resprouting is unlikely to explain the rapid decay of ravel activity as substantial regrowth did not take hold until late 2004 and 2005. Morris and Moses (1987) attributed a decrease in surficial soil movement following wildfire in Colorado to an initial depletion of fines, leaving behind a coarse lag on the soil surface, resistant to mobilization. Post-fire response in the Oregon Coast Range may be similar, but without the grain-size dependency; easily mobilized sediment stored uphill of supportive vegetation initiates following fire, leaving less-readily transported material that remains stable unless disturbed by bioturbation. Consistent with this interpretation, Bennett (1982) found that 95% of post-fire erosion occurred in the first 8 months after fire at her Oregon Coast Range study site.

Our field observations indicated that the west-facing slope in our 2003 Sulphur fire site contributed a disproportionate fraction of the dry ravel deposits. This slope may have experienced a more intense burn because the soils were drier via increased afternoon solar radiation. A study on early-season burns in Washington State (Grier, 1989) suggests that evaporative cooling at the soil surface may reduce soil heating because soil moisture must first be evaporated for temperatures to exceed 100 °C. A cooler burn on the northeast-facing slope may have protected some of the surface roots and soils from damage experienced on the hotter, drier slope. Other studies have found that post-fire erosion rates on hot, dry south-facing slopes can be up to an order of magnitude higher than on north-facing slopes (Krammes, 1960; Mersereau and Dyrness, 1972; Marques and Mora, 1992). In those studies, the difference was attributed to: (1) more and denser vegetation on north-facing slopes creating a thicker blanket of protective ash following a fire (Marques and Mora, 1992); (2) quicker recovery of vegetation on north-facing slopes (Marques and Mora, 1992); and (3) drier and, therefore, less cohesive soils on south-facing slopes (Mersereau and Dyrness, 1972). Because the Oregon Coast Range receives ample precipitation creating dense vegetation cover on all slopes, the first two factors are unlikely to be relevant to our study site. Recent process-based studies highlight the role of fire in disrupting soil aggregates, potentially making them more prone to mobilization (Ravi et al., 2006, 2007).

Significant dry ravel activity on isolated sections of steep slopes in all three of our study sites removed the soil mantle exposing bedrock. These areas featured thin soils, abundant moss, and sparse understory vegetation before the fire. Following fire, land managers expressed concern that that these “rocky meadows” would be difficult, if not impossible, to reseed. At the 1999 site and 2002 site, however, we observed abundant regrowth of moss and ferns that may facilitate soil production at these sites. Exposing the bedrock to physical and chemical weathering processes, such as periodic wetting/drying, frost action, microbial activity, and other processes, may promote rapid rates of soil production (Heimsath et al., 2001). Assuming that regenerating root systems can retain soils on these steep slopes, a calibrated soil production model for the Oregon Coast Range suggests that ∼1000 yr are required to regenerate a 20–30 cm soil mantle (Heimsath et al., 2001). More frequent and intense fires (e.g., Veblen et al., 2003) coupled with continued timber harvesting may compromise soil retention in these steep portions of the Oregon Coast Range.

Following the Oakland Hills fire of 1992, Booker et al. (1993) argued that pervasive macropores in the hydrophobic layer were generated via post-fire bioturbation from burrowing mammals. These burrowed zones served as effective hydrologic pathways to suppress perceptible post-fire runoff erosion at the site. In contrast, the patchiness of hydrophobic soil layers at our 2003 site likely results from bioturbation that occurred prior to fire because we did not observe evidence of ground disruption or small mammal activity at our trench sites. Instead, pre-fire bioturbation may have redistributed organic compounds in the soil such that conditions

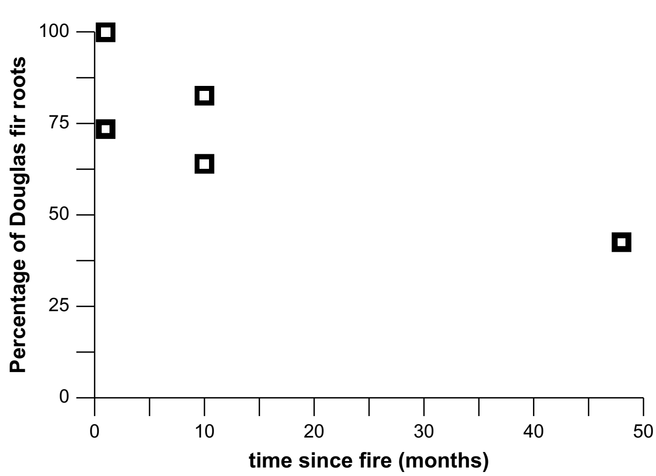

Fig. 12. Change in the fraction of Douglas-fir roots at our three study sites, expressed as a function of time since fire. After fire, Douglas-fir roots became less frequent as regrowth is dominated by low-lying vegetation.

for hydrophobic layer development were not spatially consistent. The intensity and frequency of faunal- and floral-driven soil mixing in the Oregon Coast Range, however, are poorly documented. More generally, our results are consistent with the notion that localized drop tests should be conducted broadly to characterize the continuity of hydrophobic layers.

A vast literature has documented post-harvest root strength decline in forested steeplands. Most studies highlight a period of decreased root reinforcement between 5 and 15 yr following harvest, which reflects decay of dead root systems and initial sparse regrowth of new vegetation. This period of depressed root strength left hillslopes more vulnerable to mass-wasting events in severe storms and even in moderate storms that otherwise might not have initiated landsliding (Montgomery et al., 2000). Schmidt et al. (2001) studied how land-use practices affected variation in root strength and how that variability is related to the occurrence of shallow landsliding in the Oregon Coast Range. They measured 25.6–94.3 kPa of total lateral root cohesion in natural forests, which exceeds the 6.8–23.2 kPa of root cohesion measured in industrial (or managed) forests. They found that root contribution to soil cohesion does not exceed 10 kPa in clearcuts, and that median lateral root cohesion in clearcuts is 1.5–6.7 kPa. Although the density of all roots did not vary among different sites, density of live roots was much higher in natural forests than in industrial forests, consistent with our findings.

Fire may directly affect the characteristics of root systems. Ryan et al. (1988) studied the mortality and decay of Douglas-fir (*Pseudotsuga menziesii*) 8 yr after a prescribed burn, showing that root damage is a common contributor to a tree's death, particularly given Douglas-fir's propensity to grow major lateral roots in the shallow portions of the soil column. In a study of lodgepole pines (*Pinus contorta* var. *murrayana*) growing in south-central Oregon that had survived fires since 1839, the roots and boles of the trees revealed that various fungi attacked trees through fire-damaged roots, slowing tree growth and leaving them susceptible to mountain pine beetle assault (Littke and Gara, 1986). Also, smaller diameter roots experience more direct fire-damage than larger diameter roots because their bark is thinner and offers little protection from heat due to fire (Scott et al., 1996). Because the roots measured at our 2003 site showed a more rapid strength decline than expected (Burroughs and Thomas, 1977), the trees may have had weakened root systems prior to the fire via insect infestation, fungal infections, disease, or overcrowding. Schmidt et al. (2001) encountered a stand of Douglas-fir that had been damaged by cable-yarding logging operations and exhibited depressed root reinforcement values. The diameter–strength curve for their damaged roots is similar to that for our 2003 fire site. Alternatively, the rapid decline in small-diameter root strength after wildfire may occur because these roots were concentrated at shallow depths, where they were most subject to fire damage. Our data also indicated that intense fires remove a significant amount of root reinforcement associated with low-lying vegetation that is not removed during timber harvesting.

7. Conclusion

Observations and measurements from three recent burns support the oft-cited notion that wildfire is a significant mechanism driving erosion of the Oregon Coast Range. None of our sites exhibited evidence for significant fire-driven runoff erosion through enhanced hydrophobicity. Instead, our observations suggest that discontinuities in the hydrophobic layer facilitate relatively rapid infiltration. Dry ravel is the dominant short-term erosional process at our three sites, transporting large volumes of colluvium from hillslopes to channels. A sediment budget estimated for our 2003 site shows that wildfire-induced dry ravel may account for more than 10–20% of total long-term erosion of the Oregon Coast Range, and that dry ravel erosion rates for one of our study sites are comparable to those observed in studies of post-fire geomorphic response in southern California. Our three sites demonstrate a progressive post-fire decline in root reinforcement, consistent with the notion that shallow landslides and debris flows become more likely in the years following fire. Our results highlight the role of debris flows in modulating sediment production in the Oregon Coast Range given that fire causes significant syn- and post-fire ravel-driven valley aggradation and increased shallow landslide susceptibility via reduced root reinforcement, both of which are factors that significantly affect debris flow frequency and runout.

Acknowledgments

The authors thank editors J. Clague and O. Korup for their scientific insights and efforts to produce this special volume. Reviews by S. Reneau and P. D'Odorico were highly constructive and much appreciated. The authors thank T.C. Hales and Kelly Jackson for invaluable and skillful assistance with field work. Paul Chapman of Champion, Inc. provided logistical support, facilitated site permission, and arranged for the 2003 Sulphur site to remain undisturbed until our fieldwork was complete. JJR was supported by NSF EAR-0309975.

References

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Covelo, CA. 493pp.

Almond, P., Roering, J.J., Hales, T.C., 2007. Using soil residence time to delineate spatial and temporal patterns of landscape disequilibrium. Journal of Geophysical Research—Earth Surface 112, F03S17, doi:10.1029/2006JF000568.

Anderson, H.W., Coleman, G.B., Zinke, P.J., 1959. Summer slides and winter scour—dry–wet erosion in Southern California Mountains, vol. 36. US Department of Agriculture, Forest Service Pacific Southwest Technical Paper, p. 87.

Baldwin, E.M., 1956. Geologic map of the lower Siuslaw River area, Oregon. US Geological Survey, Oil and Gas Investigation Map OM-186.

Benda, L., Dunne, T., 1997. Stochastic forcing of sediment routing and storage in channel networks. Water Resources Research 33, 2865–2880.

Benda, L., Dunne, T., 1997. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. Water Resources Research 33, 2849–2863.

Benda, L., Miller, D.J., Bigelow, P., Andras, K., 2003. Effects of post-wildfire erosion on channel environments, Boise River, Idaho. Forest Ecology and Management 178, 105–119.

Benda, L.E., 1990. The influence of debris flows on channels and valley floors in the Oregon Coast Range. USA Earth Surface Processes and Landforms 15, 457–466.

Bennett, K.A., 1982. Effects of slash burning on surface soil erosion rates in the Oregon Coast Range. M.S. Thesis, Oregon State University, Corvallis, OR, 70pp.

Beschta, R.L., 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. Water Resources Research 14, 1011–1016.

Bierman, P., Clapp, E., Nichols, K., Gillespie, A., Caffee, M., 2001. Using cosmogenic nuclide measurements in sediments to understand background rates of erosion and sediment transport. In: Harmon, R.S., Doe, W.W. (Eds.), Landscape Erosion and Evolution Modeling. Kluwer Academic Plenum, New York, pp. 89–115.

BLM, 2000. Austa Fire Emergency Fire Rehabilitation Plan and Environmental Assessment, 1792A-EA-00-01. Eugene District Bureau of Land Management.

Booker, F.A., Dietrich, W.E., Collins, L.M., 1993. Runoff and erosion after the Oakland firestorm. California Geology 46, 159–173.

Burroughs, J.E.R., Thomas, B.R., 1977. Declining root strength in Douglas-fir after felling as a factor in slope stability. Research Paper INT-190, US Department of Agriculture Forest Service, pp. 1–27.

Cannon, S.H., Bigio, E.R., Mine, E., 2001. A process for fire-related debris flow initiation, Cerro Grande fire, New Mexico. Hydrological Processes 15, 3011–3023.

Chan, M.A., Dott, J.R.H., 1983. Shelf and deep-sea sedimentation in Eocene forearc basin, Western Oregon-fan or non-fan? American Association of Petroleum Geologists Bulletin 67, 2100–2116.

Davis, M., Holbeck, C., 2001. Nuts and bolts of BAER soil and watershed assessments. In: Harmon, D. (Ed.), Crossing Boundaries in Park Management: Proceedings of the 11th Conference on Research and Resource Management in Parks and on Public Lands. The George Wright Society, Hancock, MI, pp. 166–170.

DeBano, L.F., Dunn, P.H., Conrad, C.E., 1977. Fire's effect on physical and chemical properties of chaparral soils. In: Mooney, H.A., Conrad, C.E. (Eds.), Proceedings of the Symposium on Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems. US Department of Agriculture Forest Service, Washington, DC, pp. 65–74.

Dietrich, W.E., Dunne, T., 1978. Sediment budget for a small catchment in mountainous terrain. Zeitschrift fur Geomorphologie, Supplement 29, 191–206.
Doehring, D.O., 1968. The effects of fire on geomorphic processes in the San Gabriel Mountains. Rocky Mountain Geology 7, 43–65.
Florsheim, J.L., Keller, E.A., Best, D.W., 1991. Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, southern California. Geological Society of American Bulletin 103, 504–511.
Gabet, E.J., 2003. Sediment transport by dry ravel. Journal of Geophysical Research—Solid Earth 108, doi:10.1029/2001JB001686.
Gray, D.H., Leiser, A.T., 1982. Biotechnical Slope Protection and Erosion Control. Van Nostrand Rheinhold, New York. 271pp.
Gray, D.H., Sotir, D.B., 1996. Biotechnical and soil bioengineering slope stabilization. Wiley, New York. 378pp.
Grier, C.C., 1989. Effects of prescribed springtime underburning on production and nutrient status of a young ponderosa pine stand. In: Tecle, A., Covington, W.W., Hamre, R.H. (Technical Coordinators), Proceedings of the Multiresource Management of Ponderosa Pine Forests, 14–16 November 1989, Flagstaff, AZ. USDA Forest Service General Technical Report RM-185, pp. 71–76.
Heimsath, A.M., Dietrich, W.E., Nishiizumi, K., Finkel, R.C., 2001. Stochastic processes of soil production and transport: erosion rates, topographic variation and cosmogenic nuclides in the Oregon Coast Range. Earth Surface Processes and Landforms 26, 531–552.
Heller, P., Peterman, Z.E., O'Neil, J.R., Shafiqullah, M., 1985. Isotopic provenance of sandstones from the Eocene Tyee Formation, Oregon Coast Range. Geological Society of America Bulletin 96, 770–780.
Heller, P.L., Dickinson, W.R., 1985. Submarine ramp facies model for delta-fed, sand-rich turbidite systems. AAPG Bulletin 69, 960–976.
Kelsey, H.M., Ticknor, R.L., Bockheim, J.G., Mitchell, C.E., 1996. Quaternary upper plate deformation in coastal Oregon. Geological Society of America Bulletin 108, 843–860.
Krammes, J.S., 1960. Erosion from mountain side slopes after fire in southern California. US Forest Service Research Note, PSW-171, 8pp.
Lancaster, S.T., Casebeer, N.E., 2007. Sediment storage and evacuation in headwater valleys at the transition between debris-flow and fluvial processes. Geology 35, 1027–1030.
Lancaster, S.T., Hayes, S.K., 2003. Effects of wood on debris flow runout in small mountain watersheds. Water Resources Research 39, doi:10.1029/2001WR001227.
Legleiter, C.J., Lawrence, R.L., Fonstad, M.A., Marcus, W.A., Aspinall, R., 2003. Fluvial response a decade after wildfire in the northern Yellowstone ecosystem: a spatially explicit analysis. Geomorphology 54, 119–136.
Littke, W.R., Gara, R.I., 1986. Decay of fire-damaged lodgepole pine in southcentral Oregon. Forest Ecology and Management 17, 279–287.
Long, C.J., Whitlock, C., Bartlein, P.J., Millspaugh, S.H., 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Canadian Journal of Forest Research 28, 774–787.
Lovell, J.P.B., 1969. Tyee formation: undeformed turbidites and their lateral equivalents: mineralogy and paleogeography. Geological Society of American Bulletin 80, 9–22.
Malmon, D.V., Reneau, S.L., Katzman, D., Lavine, A., Lyman, J., 2007. Suspended sediment transport in an ephemeral stream following wildfire. Journal of Geophysical Research 112, F02006, doi:10.1029/2005JF000459.
Marques, M.A., Mora, E., 1992. The influence of aspect on runoff and soil loss in a Mediterranean burnt forest. Catena 19, 333–344.
Martin, Y.E., 2007. Wildfire disturbance and shallow landsliding in coastal British Columbia over millennial time scales: a numerical modelling study. Catena 69, 206–219.
McNabb, D.H., Swanson, F.J., 1990. Effects of fire on soil erosion. In: Walstad, D., Radosevich, S.R., Sandberg, D.V. (Eds.), Natural and Prescribed Fire in Pacific Northwest Forests. Oregon State University Press, Corvallis, OR, pp. 159–176.
McNabb, D.H., Gaweda, F., Froehlich, H.A., 1989. Infiltration, water repellency, and soil moisture content after broadcast burning in a forest site in southwest Oregon. Journal of Soil and Water Conservation 44, 87–90.
McNeill, L.C., Goldfinger, C., Kulm, L.D., Yeats, R.S., 2000. Tectonics of the Neogene Cascadia forearc basin: investigations of a deformed late Miocene unconformity. Geological Society of America Bulletin 112, 1209–1224.
Mersereau, R.C., Dyrness, C.T., 1972. Accelerated mass wasting after logging and slash burning in western Oregon. Journal of Soil and Water Conservation 27, 112–114.
Mitchell, C.E., Vincent, P., Weldon, R.J., Richards, M., 1994. Present-day vertical deformation of the Cascadia margin, Pacific Northwest, United States. Journal of Geophysical Research 99, 12,257–12,277.
Montgomery, D.R., 2001. Slope distributions, threshold hillslopes, and steady-state topography. American Journal of Science 301, 432–454.
Montgomery, D.R., Schmidt, K.M., Greenberg, H., Dietrich, W.E., 2000. Forest clearing and regional landsliding. Geology 28, 311–314.
Moody, J.A., Martin, D.A., 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. Earth Surface Processes and Landforms 26, 1049–1070.
Morris, S.E., Moses, T.A., 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. Annals of the Association of American Geographers 77, 245–254.
Munns, E.N., 1920. Chaparral cover, run-off, and erosion. Journal of Forestry 18, 806–814.
Nitschke, C.R., 2005. Does forest harvesting emulate fire disturbance? A comparison of effects on selected attributes in coniferous-dominated headwater systems. Forest Ecology and Management 214, 305–319.
Personius, S.F., 1995. Late Quaternary stream incision and uplift in the forearc of the Cascadia subduction zone, western Oregon. Journal of Geophysical Research 100, 20,193–20,210.
Personius, S.F., Kelsey, H.M., Grabau, P.C., 1993. Evidence for regional stream aggradation in the Central Oregon Coast Range during the Pleistocene–Holocene transition. Quaternary Research 40, 297–308.
Ravi, S., D'Odorico, P., Herbert, B., Zobeck, T., Over, T., 2006. Enhancement of wind erosion by fire-induced water repellency. Water Resources Research 42, doi:10.1029/2006WR004895.
Ravi, S., D'Odorico, P., Zobeck, T., Over, T., Collins, S.L., 2007. Feedbacks between fires and wind erosion in heterogeneous arid lands. Journal of Geophysical Research—Earth Surface 112, doi:10.1029/2007JG000474.
Reneau, S.L., Dietrich, W.E., 1990. Depositional history of hollows on steep hillslopes, coastal Oregon and Washington. National Geographic Research 6, 220–230.
Reneau, S.L., Dietrich, W.E., 1991. Erosion rates in the Southern Oregon Coast Range: evidence for an equilibrium between hillslope erosion and sediment yield. Earth Surface Processes and Landforms 16, 307–322.
Reneau, S.L., Dietrich, W.E., Donahue, D.J., Jull, A.J.T., Rubin, M., 1990. Late Quaternary history of colluvial deposition and erosion in hollows, Central California Coast Ranges. Geological Society of America Bulletin 102, 969–982.
Rice, R.M., 1982. Sedimentation in chaparral: how do you handle the unusual events? In: Swanson, F.J., Janda, R.J., Dunne, T., Swanston, D.N. (Eds.), Sediment Budgets and Routing in Natural Systems. Pacific Northwest Forest and Range Experimental Station, USDA Forest Service, pp. 39–49.
Rice, R.M., Corbett, E.S., Bailey, R.G., 1969. Soil slips related to vegetation, topography, and soil in Southern California. Water Resources Research 5, 637–659.
Roering, J.J., Gerber, M., 2005. Fire and the evolution of steep, soil-mantled landscapes. Geology 33, 349–352.
Roering, J.J., Kirchner, J.W., Dietrich, W.E., 1999. Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology. Water Resources Research 35, 853–870.
Roering, J.J., Schmidt, K.M., Stock, J.D., Dietrich, W.E., Montgomery, D.R., 2003. Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range. Canadian Geotechnical Journal 40, 237–253.
Roering, J.J., Kirchner, J.W., Dietrich, W.E., 2005. Characterizing structural and lithologic controls on deep-seatedlandsliding: implications for topographic relief and landscape evolution in the Oregon Coast Range, USA. Geological Society of America Bulletin 117, 654–668.
Ryan, K.C., Peterson, D.L., Reinhardt, E.D., 1988. Modeling long-term fire-caused mortality of Douglas-fir. Forest Science 34, 190–199.
Schmidt, J.C., 1995. Geomorphic response to wildfire following timber harvest, South Fork Cow Creek, Oregon. US Geological Survey Water Resources Investigation Report 94-4122, 17pp.
Schmidt, K.M., Roering, J.J., Stock, J.D., Dietrich, W.E., Montgomery, D.R., Schaub, T., 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal 38, 995–1024.
Scott, D.W., Szymoniak, J., Rockwell, V., 1996. Entomological concerns regarding burn characteristics and fire effects on tree species during prescribed landscape burns: burn severity guidelines and mitigation measures to minimize fire injuries. US Department of Agriculture Forest Service, PNW Research Station Technical Paper.
Shakesby, R.A., Doerr, S.H., 2006. Wildfire as a hydrological and geomorphological agentEarth-Science Reviews 74, 269–307.
Shakesby, R.A., Wallbrink, P.J., Doerr, S.H., English, P.M., Chafer, C.J., Humphreys, G.S., Blake, W.H., Tomkins, K.M., 2007. Distinctiveness of wildfire effects on soil erosion in south-east Australian eucalypt forests assessed in a global context. Forest Ecology and Management 238, 347–364.
Spina, A.P., Tormey, D.R., 2000. Postfire sediment deposition in geographically restricted steelhead habitat. North American Journal of Fisheries Management 20, 562–569.
Spittler, T.E., 1995. Fire and the debris flow potential of winter storms. In: Keeley, J.E., Scott, T. (Eds.), Brushfires in California Wildlands: Ecology and Resource Management. International Association of Wildland Fire, Fairfield, WA, pp. 113–120.
Stock, J., Dietrich, W.E., 2003. Valley incision by debris flows: evidence of a topographic signature. Water Resources Research 39, doi:10.1029/2001WR001057.
Stock, J., Dietrich, W.E., 2006. Erosion of steepland valleys by debris flows. Geological Society of America Bulletin 118, 1125–1148.
Swanson, F.J., 1981. Fire and geomorphic processes. In: Proceedings, Fire Regimes and Ecosystems Conference. US Department of Agriculture, Forest Service, General Technical Report. WO-26, Honolulu, HI, pp. 401–420.
Swezy, D.M., Agee, J.K., 1990. Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. Canadian Journal of Forest Research 21, 626–634.
Veblen, T.V., Baker, W.L., Montenegro, G., Swetnam, T.W. (Eds.), 2003. Fire and Climatic Change in Temperate Ecosystems of the Western Americas Ecological Studies, vol. 160. Springer, Berlin 444pp.
Wells II, W.G., 1981. Some Effects of Brush Fires on Erosion Processes in Coastal Southern California. Erosion and Sediment Transport in Pacific Rim Steeplands. International Association of Hydrological Sciences, Christchurch, NZ, pp. 305–342.

Wells II, W.G., 1987. The effects of fire on the generation of debris flows in Southern California. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris Flows/Avalanches: Process, Recognition, and Mitigation. Geological Society of America, Boulder, CO, pp. 105–114.

Wohlgemuth, P.M., Hubbert, K.R., Robichaud, P.R., 2001. The effects of log erosion barriers on post-fire hydrologic response and sediment yield in small forested watersheds, Southern California. Hydrological Processes 15, 3053–3066.

Wondzell, S.M., King, J.G., 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. Forest Ecology and Management 178, 75–87.

Wu, T.H., 1984. Effect of Vegetation on Slope Stability, Soil Reinforcement and Moisture Effects on Slope Stability. Transportation Research Board, Washington, DC, pp. 37–46.

Wu, T.H., 1995. Slope stabilization. In: Morgan, R.P.C., Rickson, R.J. (Eds.), Slope Stabilization and Erosion Control: A Bioengineering Approach. E & FN Spon, London, pp. 221–264.